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An analysis of coastal and inland fatalities in landfalling US hurricanes

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Abstract Improvements in hurricane forecasts allowing for more timely evacuations from storm-surge zones are credited with reducing lethality of US landfalling hurricanes. The deadly reach of a hurricane, however, is not limited to storm-surge zones. About 80% of direct US hurricane fatalities since 1970 occurred outside of landfall counties, with most of these fatalities caused by inland flooding. We construct a geographic information system database combining the location and cause of fatalities, estimated wind speeds, and rainfall amounts for the entire track of the storm for landfalling US hurricanes between 1970 and 2007. We analyze the determinants of total fatalities and deaths due to freshwater drowning and wind. Inclusion of inland fatalities results in no downward trend in lethality over the period, in contrast to prior research. Local storm conditions significantly affect lethality, as one-inch and one-knot increases in rainfall and wind increase total fatalities by 28 and 4%. Rainfall significantly increases freshwater-drowning deaths and is insignificant for wind deaths, while the opposite relation holds for wind speed. While coastal counties do not exhibit a significantly higher amount of lethality risk versus inland counties for total or wind-driven fatalities, freshwater-drowning fatalities occur most frequently in inland counties along the center of the storm path and its outer county tiers as we have defined them.

Keywords Hurricanes · Fatalities · Freshwater drowning · Rainfall · Wind field

JEL Classifications Q54

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1 Introduction

Existing analyses demonstrate a decline in the lethality of hurricanes hitting the United States over time (Kunkel et al. 1999; Rappaport 2000; Sadowski and Sutter 2005; Blake et al. 2007). Figure 1 illustrates this general trend with the total number of fatalities by decade since 1900. Fatalities exceeded 1,000 in each of the first three decades of the twentieth century, but declined after 1930 and were under 200 for each of the final decades of the century. The catastrophe of hurricane Katrina has at least temporarily reversed this trend. Over 90% of hurricane fatalities on land prior to 1970 have been attributed to storm surge (American Meteorological Society 1973). Researchers credit improvements in hurricane forecasts allowing more timely evacuations from storm-surge zones prior to landfall for the declining lethality apparent in Fig. 1 (Rappaport 2000; Willoughby et al. 2007).

The deadly reach of a hurricane is not limited to storm-surge zones. Hurricanes pose a variety of threats, including storm surge, high winds, rough seas, tornadoes, and freshwater flooding from heavy rainfall. Indeed, Rappaport (2000) found that the majority of tropical cyclone–related fatalities between 1970 and 1999 occurred inland due to freshwater flooding. Czajkowski and Kennedy (2010) further showed that roughly 80% of direct hurricane fatalities since 1970, excluding Hurricane Katrina, occurred outside of the National Hurricane Center (NHC) identified affected landfall counties. Further reductions in the lethality of hurricanes will require extending warnings, media attention, and public response beyond the area of coastal landfall (Elsberry 2002; Zandbergen 2009).

While observers agree on the goal of reducing hurricane impacts, to do so in a cost-effective manner requires an accurate assessment of the causes of the impacts (Peacock et al. 2004; MMC 2005; Shultz et al. 2005). Yet, little is known about the determinants of fatalities across a hurricane's path, and particularly inland fatalities. Existing studies of US hurricane fatalities examine either total fatalities (Sadowski and Sutter 2005) or coastal fatalities (Price 2008; Czajkowski and Kennedy 2010). Rappaport (2000, p. 2072) suggests

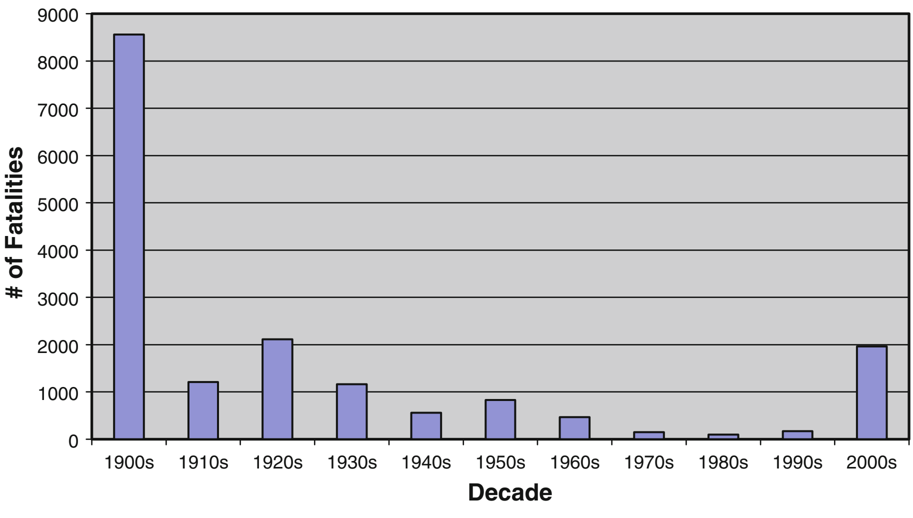

Fig. 1 US hurricane fatalities by decade. US fatalities in landfalling hurricanes from 1900 to 2009, aggregated by decade. *Source* Pielke et al. (2008) and NHC annual summaries. Hurricane Katrina accounts for 93% of the total 1,963 fatalities in the 2000s

the need for "societal impact studies" to allow a reduction in loss of life in inland areas. We begin such an analysis by empirically modeling hurricane fatalities in coastal and inland counties between 1970 and 2007.

We construct a geographic information system (GIS) database overlaying the location and cause of each fatality onto a three-tiered classification of affected counties (primary, secondary, and tertiary) across the entire track of the storm. Our GIS database incorporates estimated wind and precipitation by county across the storm path and we model fatalities as a function of the assumed localized storm conditions; notably, previous research has called for a better understanding of the impact from hurricane landfall precipitation (Elsberry 2002; Knight and Davis 2007), and this is the first study to date to include the impact of rainfall on hurricane fatalities. In contrast to previous studies, inclusion of inland fatalities results in no downward trend in lethality over the period. Local storm conditions are significant drivers of fatalities; a one-knot increase in wind increases total fatalities by 4% and wind fatalities by 7%, while a one-inch increase in rainfall increases total fatalities by 28% and freshwater-drowning deaths by 45%. Interestingly, coastal counties do not exhibit a significantly higher amount of lethality risk versus inland counties for total or wind-driven fatalities. However, freshwater-drowning fatalities occur most frequently in inland counties along the center of the storm path and its outer county tiers as we have defined them.

The remainder of the paper proceeds as follows. Section 2 describes the construction of the database used in this analysis. We detail the zero-inflated regression model employed to analyze fatalities in Sect. 3. Section 4 then presents the empirical analysis, while Sect. 5 offers concluding comments and directions for future research.

2 Coastal and inland hurricane data

We construct a county-level database for our analysis, with the unit of observation being a county affected by a given storm. Hurricane fatalities have been identified at the county level, and a county level analysis also allows us to control for variation in wind and rain across the storm area. Czajkowski and Kennedy (2010) constructed a dataset for the NHC and identified affected landfall counties associated with their 68 classified US hurricanes occurring between 1970 and 2007. We modify and expand this dataset to include all pertinent coastal counties (i.e., not only those identified by the NHC as being affected landfall counties), inland counties, the count of fatalities in each county by cause, and storm-related wind values and precipitation amounts by county. The wind and rain data are available for 62 of the 68 hurricanes over the period.[1] Following Czajkowski and Kennedy's (2010) hurricane risk perspective, a landfalling "hurricane" for this analysis is any tropical cyclone that attained hurricane status during its lifetime regardless of its status at landfall. Nine of the 62 landfalling hurricanes in this analysis caused landfall in the United States as a tropical storm.[2] Other landfalling tropical storms have been excluded from the analysis even though some have resulted in major flooding and loss of life. Finally, our analysis excludes Hurricane Katrina.

[1] Missing data necessitated the exclusion of Hurricanes Celia (1970), Emily (1993), Gustav (2002), Alex (2004), Dennis (2005), and Ophelia (2005).

[2] These are Dennis (1981), Dennis (1999), Gabrielle (2001), Gilbert (1988), Gordon (1994), Gordon (2000), Isidore (2002), Kyle (2002), and Mitch (1998).

2.1 Coastal and inland counties

The NHC identifies directly and indirectly[3] affected coastal counties from the 175 coastal counties along the Gulf of Mexico and Atlantic coasts from Texas to Maine for landfalling hurricanes since 1900 (NHC Re-Analysis Project 2008a). No roster of affected inland counties, however, exists. We use the NHC coastal county list in conjunction with the GIS Historical Hurricane Tracks dataset (NOAA Coastal Services Center 2008) to identify the coastal and inland counties for this analysis as described below, with coastal counties further delineated by affected (direct or indirect) landfall counties.

The GIS Historical Hurricane Tracks dataset (NOAA Coastal Services Center 2008) provides the center of the storm across its entire path for each of our 62 landfalling hurricanes. We modify these center paths in two main ways to identify coastal and inland-affected counties. First, storm-related impacts are not only limited to the center path of the storm. We account for a hurricane's reach by designating primary, secondary, and tertiary counties along each storm's center path. Primary counties are those traversed by the center of the storm, secondary counties are those adjacent to primary counties, and tertiary counties are adjacent to secondary counties. From this per storm primary, secondary, and tertiary county breakdown, coastal and inland counties are identified. Coastal counties are those from the overall NHC list of 175 coastal counties falling within our constructed primary, secondary, and tertiary hurricane swath, while inland counties are all non-coastal counties within our constructed hurricane swath. Coastal counties are further delineated as being an affected landfall coastal county or not according to the NHC affected landfall county classification.[4] Second, only the center path of the storm when over land is utilized in order to make straightforward and consistent the distinction between our defined county types. Thus, counties potentially affected when a storm was over water but skirting along the coast (e.g., Hurricane Floyd 1999) are not included. The 62 hurricane center paths over land utilized in this analysis are illustrated in Fig. 2.

Figure 3 illustrates the storm center path and designation of primary, secondary, and tertiary coastal and inland counties for Hurricane Opal in 1995, which made landfall near Pensacola Beach, Florida, and eventually tracked into Canada. Of the 7 identified coastal counties illustrated, 5 counties in Florida were affected landfall counties (Bay, Escambia, Okaloosa, Santa Rosa, and Walton) with the two counties in Alabama (Baldwin and Mobile) being coastal counties not affected by hurricane landfall as identified by the NHC. Similar hurricane swaths are constructed for each of the 62 hurricanes in the analysis. From this methodology, our 62 landfalling hurricanes result in a total of 9,326 county-storm observations. Table 1 breaks down the county-storm observations by type. Primary, secondary, and tertiary counties account for 23, 38, and 39% of the total observations, respectively, with a total of 1,337 coastal county observations versus 7,989 inland county observations. Of these 1,337 coastal county observations, nearly 25% are from designated affected landfall counties.

[3] An indirectly affected county is "a county/parish/borough that experienced fringe affects" (NHC Re-Analysis Project 2008a, b).

[4] For the 9 storms that made landfall as a tropical storm included in this analysis, explicit county strikes are not available from the re-analysis project. For these storms, affected landfall counties are limited to the primary coastal counties for the affected landfall states identified in the re-analysis project (NHC Re-Analysis Project 2008b).

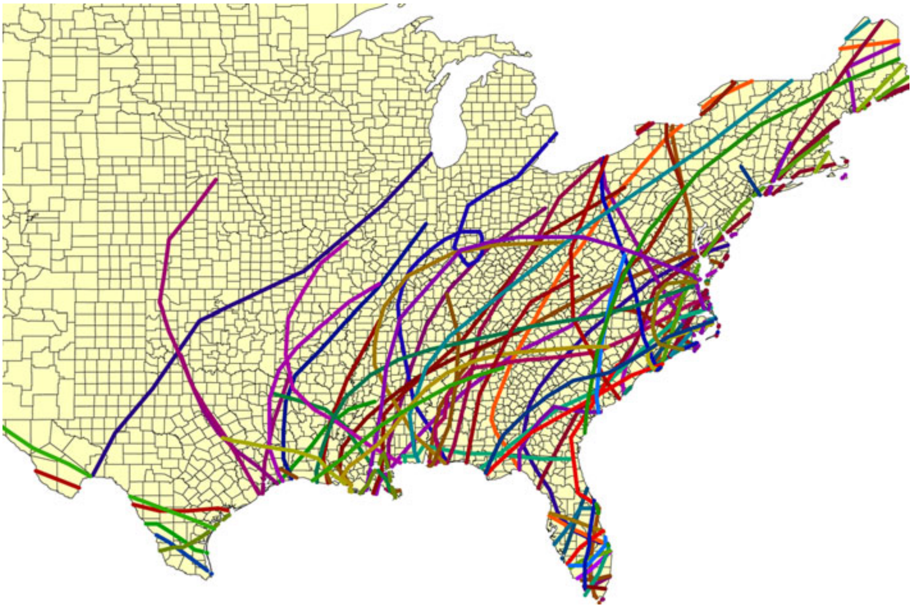

Fig. 2 Center paths over land for designated 62 landfalling hurricanes

2.2 Coastal and inland fatalities and causes

We include all fatalities in the hurricane path identified previously. Our fatality information comes from Rappaport (2000) and Czajkowski and Kennedy (2010). A total of 483 fatalities from these studies were attributed to one of the 62 hurricanes in our dataset. The county was not identified for 106 of these fatalities, while 194 occurred outside of our designated coastal and inland counties included in our analysis. This leaves 183 fatalities for analysis here.[5] Figure 4 illustrates the assignment of fatalities along the path for Hurricane Opal. Nine fatalities occurred in Opal in eight different counties, but only five of these nine fatalities occurred within our designated coastal and inland storm swath. Of the five Opal fatalities falling within our hurricane swath, 80% occur in inland counties and 40% are in primary counties.

Table 2 describes the incidence of fatalities across primary, secondary, and tertiary counties for both coastal (affected landfall and non-affected landfall) and inland county types. Coastal primary and inland tertiary counties have the largest totals. Overall, 43% of fatalities occur in primary counties, while 52% of fatalities occur in inland counties. A higher proportion of coastal fatalities occur in primary counties (especially for affected landfall counties), while inland fatalities have a higher proportion occurring in tertiary counties but are more evenly divided between primary, secondary, and tertiary counties. Although slightly more total fatalities occur inland, inland counties account for nearly 86%

[5] Seventy-five of the 194 fatalities occurring in known counties outside of our constructed swath were from three storms—Agnes 1972 (58%), Floyd 1999 (12%), and Chantal 1989 (5%). These missing data are mainly associated with the portion of the hurricane being over water, which we excluded. Roughly 15% of the 194 missing fatalities can be attributed to the swath overland plausibly not being large enough. The remaining 10% is attributed to fatalities that occurred very far from the point of landfall, e.g., Dennis in 1999 had 3 fatalities associated with Florida coastal counties, while landfall occurred in North Carolina.

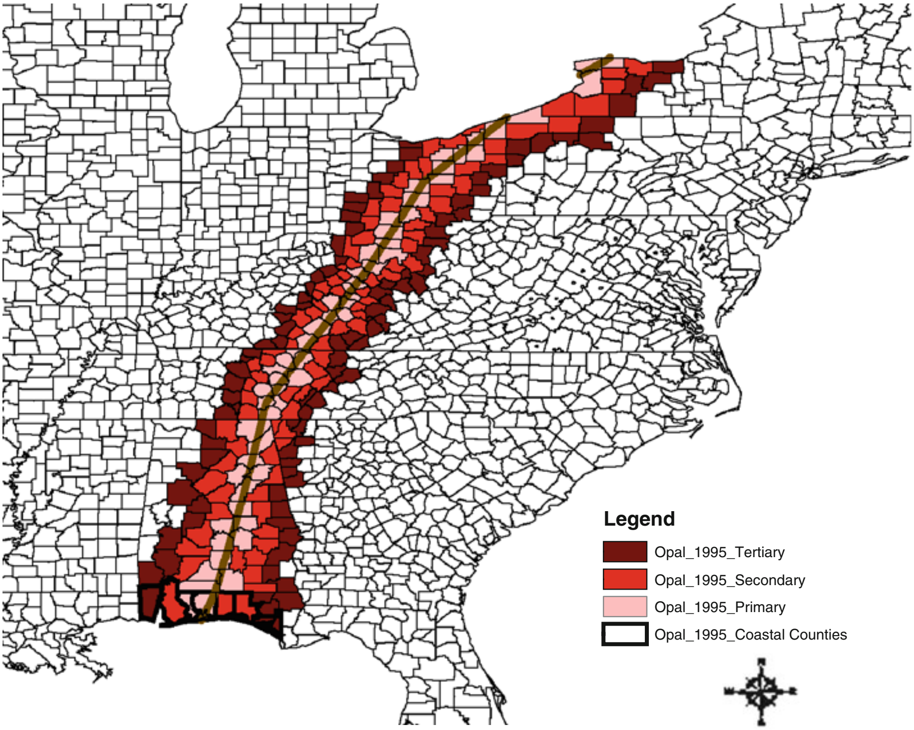

Fig. 3 Coastal and inland counties for Hurricane Opal in 1995

Table 1 Total primary, secondary, and tertiary counties by geographical distinction

	Coastal			Inland	Total
	Affected landfall	Not affected landfall	Total coastal		
Primary	148	257	405	1,757	2,162
Secondary	116	376	492	3,072	3,564
Tertiary	58	382	440	3,160	3,600
Total	322	1,015	1,337	7,989	9,326

of the county-storm observations, and so fatalities per affected county are greater for coastal counties (0.06 vs. 0.01). This difference is even greater for affected landfall coastal counties versus inland counties (0.16 vs. 0.01).

Rappaport (2000) and Czajkowski and Kennedy (2010) also report fatalities segmented by cause of death. Table 3 reports the distribution of fatalities in our dataset by cause of death in total and for coastal and inland counties. All but 6 deaths have an identified cause, with freshwater drowning (41%) and wind (33%) being the two most frequent types.[6] Not

[6] The county was identified for 194 fatalities excluded from our analysis due to distance from the storm path, and the cause of death was identified for 156 of these fatalities. The most common cause for these excluded fatalities is freshwater drowning (72%).

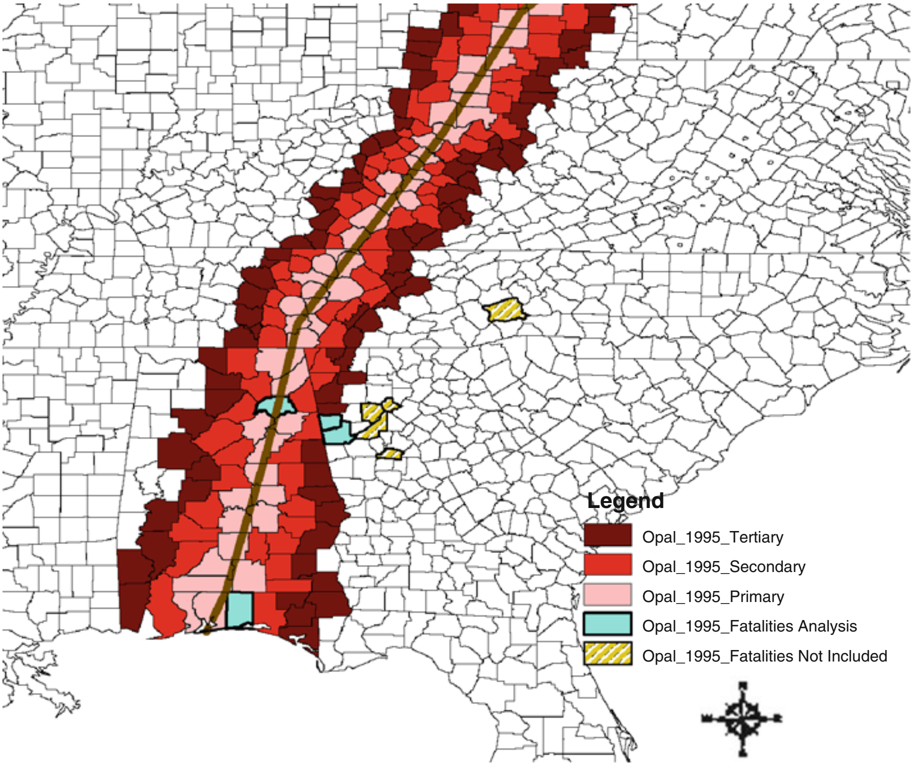

Fig. 4 Fatalities associated with Hurricane Opal in 1995

Table 2 Total fatalities by coastal and inland county type

County type	Landfall	Primary	Secondary	Tertiary	Total	% of total
Coastal	Affected	31	12	8	51	28
	Not affected	17	10	10	37	20
Coastal total		48	22	18	88	48
Inland	N/A	31	28	36	95	52
Total # of fatalities		79	50	54	183	100
% of total		43	27	30	100	

surprisingly, 79% of the freshwater-drowning fatalities occur in inland counties. Even though hurricanes weaken significantly in wind strength after making landfall (Kaplan and Demaria 1995, 2001), 47% of the wind deaths also occurred in inland counties.

2.3 Related wind and precipitation storm data

Freshwater drowning and wind account for nearly 75% of fatalities in our dataset, highlighting the importance of incorporating wind and precipitation measures into the analysis. We obtain individual county wind speed observations by overlaying the GIS Historical

Table 3 Total fatalities by coastal and inland county type and cause

County type	Freshwater drowning	Wind	Offshore drowning	Surf drowning	Tornado	Surge drowning	Unknown	Total
Coastal	16	32	16	12	3	5	4	88
Inland	59	28	0	0	6	0	2	95
Total	75	60	16	12	9	5	6	183

Hurricane Tracks dataset (NOAA Coastal Services Center 2008) maximum sustained wind speed (MSW) measurements in knots, which are issued in conjunction with the latitude and longitude coordinates for the entire center of the storm path onto our set of counties. A number of assumptions and modifications are made to this data in order to construct our specific county wind speed values for the designated primary, secondary, and tertiary hurricane swath. First, we assume that the MSW issued in conjunction with the latitude and longitude coordinates of the center of the storm (our primary counties) are congruent and are assigned at 100% value to the entire matching primary county. This congruency may not necessarily hold as the MSW values listed for the storm best track are simply those associated with the storm; the exact location of those MSW values is not specifically indicated or even generally known.[7] Second, depending on the speed of the forward motion of the storm, more than one MSW value may be associated with our designated primary county. We average the values for counties with more than one wind speed data point. Third, the NOAA track dataset MSW values that we use for our primary counties along the center of the track do not provide MSW values for the designated secondary and tertiary counties along the entire storm path.

Hurricane winds tend to decay away from the center of the storm. The decaying nature of MSWs at landfall is characterized from a symmetric perspective (Kimball and Mulekar 2004) and non-symmetric perspective (Bell and Ray 2004), with the radii of hurricane and damaging force winds shown to be generally declining as the intensity of the storm decreases. A number of parametric models have been developed to estimate the extent of hurricane wind field radii and decay rates (Kaplan and Demaria 1995, 2001; Bell and Ray 2004; Gray and Klotzbach 2005; Nordhaus 2006; Zandbergen 2009; Kruk et al. 2010). For example, from the wind radii model developed by Gray and Klotzbach (2005), winds from a 100-knot category 3 major hurricane would maintain 100% of their level of intensity for a radial distance up to 30 km (19 mi), but would decrease to 65% of this value (65 knots) at a radial distance of 71 km (44 mi), and 35% of this at a radial distance of 213 km (132 miles). These rates of decay are higher, and the extent of winds smaller, for less intense storms. Relatively comparable wind radii/rates of decay are shown in the raw data in Kimball and Mulekar (2004) and Bell and Ray (2004), as well as the outcomes illustrated from the models developed in Kaplan and Demaria (1995) and Nordhaus (2006).[8]

Nearly 50% of our primary county wind speed estimates are below tropical storm strength (35 knots), and 82% are below hurricane strength (64 knots). Based on the size of the counties in our dataset, the average width of our counties is approximately 25 miles. Our analysis essentially focuses on a swath approximately 75 miles on either side of the center path. Based on the general results from these wind radii studies that have category 3

[7] Personal communication with James Franklin of the NHC.

[8] We verified this by calculating wind radii across the different hurricane category wind speed levels from the models developed in Kaplan and Demaria (1995), Gray and Klotzbach (2005), and Nordhaus (2006).

Table 4 Distribution of wind speeds and fatalities

Wind speed (in knots)	Storm classification	# of events	% of events	Fatalities	Fatalities per event
0–33	Tropical depression	6,649	71.3	41	0.006
34–47	Tropical storm (TS)	1,317	14.1	39	0.030
48–63	Severe TS	830	8.9	26	0.031
64–82	Category (CAT) 1 hurricane	351	3.8	27	0.077
83–95	CAT 2 hurricane	106	1.1	15	0.142
96–113	CAT 3 hurricane	53	0.6	1	0.019
114–135	CAT 4 hurricane	20	0.2	34	1.700
Total		9,326	100.0	183	0.020

Category 5 values were not available from our dataset as the category 5 values from Hurricane Andrew occurred over water

hurricane force winds at 65% of the maximum value at a radial distance of 71 km (44 mi), decaying more rapidly for less intense storms, we initially conservatively assign wind values of 75 and 50% of the center track value for our secondary and tertiary counties, respectively, along the entire storm path. To illustrate, when the center track wind is 110 knots, the primary county is assigned a MSW of 110 knots, with the adjacent secondary and tertiary counties assigned 83 and 55 knots, respectively. We follow Kimball and Mulekar (2004) in this analysis in assigning symmetric percentage values to the secondary and tertiary counties on the right- and left-hand side of the storms. Bell and Ray (2004) also found that wind radii are fairly symmetric for hurricanes up to category 2 levels, which represent the vast majority of our primary county observations. Given the limited number of studies on the decay of inland winds (Kruk et al. 2010), we find this method to be straightforward and tractable for this initial analysis. We do, however, also conduct a number of sensitivity analyses for the decay percentage values later.

Table 4 reports the distribution of our county event observations by wind speed category. The categories are reported in knots and correspond to winds less than tropical storm strength, weak and strong tropical storm strength, and categories 1, 2, 3, and 4 on the Saffir–Simpson Hurricane Scale. Over 70% of our county observations have winds of less than tropical storm strength, while less than 6% involve hurricane force winds. The table also reports fatalities per county event in each category, which increase with each category except the 96–113 knot range, where the fatality rate is lower than for tropical storm force winds. Fatalities per county event for a category 4 hurricane exceed the rate for subtropical force winds by more than two orders of magnitude.

Hurricane rainfall data were obtained from David Roth of the Hydrometeorological Prediction Center (HPC 2009). The data reports total inches of rain by measurement location over the period of rainfall from the hurricane. We follow Knight and Davis (2007) and take the HPC total rainfall data as is for each storm, not attempting for instance to parse out rainfall that may have been associated with a frontal system that preceded the storm. We do modify the HPC rainfall data in two main ways. First, after uploading the data into our GIS database, we interpolate the rainfall data via a kriging interpolation scheme[9] in order to account for the inherently variable nature of the collected rainfall data

[9] An inverse distance-weighted interpolation scheme was also conducted and compared with the results of the kriging interpolation methodology.

Table 5 Distribution of rainfall amounts and fatalities

Rainfall amount (in inches)	# of events	% of events	Fatalities	Fatalities per event
0–3	5,917	63.5	23	0.004
3–6	2,763	29.6	70	0.025
6–9	499	5.3	48	0.096
9–12	95	1.0	16	0.168
>12	52	0.6	26	0.500
Total	9,326	100.0	183	0.020

over space and time as well as a large number of counties with missing rainfall values. Second, we then join the interpolated rainfall data to our primary, secondary, and tertiary county swaths to yield a single mean total rainfall value per county. In this way, while the interpolation scheme has captured the impact of rainfall values near to the boundary of our swath, the majority of rainfall values outside of our swath have been excluded. Table 5 reports the distribution of county events and fatalities per event by rainfall amount. Nearly two-thirds of the county events involved rainfall of 3″ or less, while less than 1% of county events had storm rainfall in excess of 12″. The lethality of heavy rainfall is readily apparent in Table 5. Fatalities per event were 0.004 for events with 3″ or less of rain and increase in each category to 0.500 for 12″ or more of rain.

2.4 Data limitations

As Rappaport (2000, p. 2067) states, "The most severe weather usually covers a small area near the circulation center that diminishes in extent when a tropical cyclone moves inland". Existing studies of various hurricane impacts at the state and county level focus their analysis on counties close to the center of the storm such as in Costanza et al. (2008) that construct 100 km × 100 km coastal and inland-affected county swaths, or Deryugina (2011) that finds for major hurricanes average building damages for centrally affected counties (similar to our primary counties) to be 65 times higher than average building damages in affected peripheral counties along the storm's path. Consequently, we feel that this initial analysis focused on our designated primary, secondary, and tertiary county swath is warranted.

However, a significant number of fatalities in known counties are not included in our designated hurricane swath, many of these attributable to an inland flooding cause of death. This is even more pertinent given the findings of existing studies on hurricane precipitation amounts that find hurricane precipitation to be highly spatially variable in nature and dependent on specific attributes of the storm such as size and speed of forward motion, not necessarily connected merely to the strength and center path of the storm (Elsberry 2002; Konrad et al. 2002; Atallah et al. 2007; Matyas 2010). Furthermore, flooding itself is often dependent upon the timing and spatial distribution of rainfall (Konrad 2001; Konrad et al. 2002), not purely the total rainfall amount as we utilize here. And although we have interpolated our rainfall data, the interpolation still does not account for the specific topography of the various counties, which also impacts the timing and spatial distribution of rainfall. Finally, the flawed nature of natural hazard fatality data is well recognized (Guha-Sapir et al. 2004; Tschoegl et al. 2006; Gall et al. 2009), and these concerns apply here as well. We note these as limitations to our initial analysis and incorporate them into the final discussion of our results.

3 Empirical methods

The dependent variable in our empirical analysis, $\text{Fatalities}_{i,j,t}$, is the count of fatalities in county, *i*, for hurricane, *j*, in year, *t*. We propose the following model for hurricane fatalities:

$$\text{Fatalities}_{i,j,t} = f\left(\text{WR}_{i,j,t}, G_{i,j,t}, T_t, S_{i,j,t}\right) \quad (1)$$

where WR are the wind and rain values, *G* is a vector of geography variables, *T* is a vector of dummy variables to control for the year of landfall, and *S* is a vector of socioeconomic variables. The geography, time, and socioeconomic variables will be introduced and defined presently.

Fatalities takes on non-negative integer values (e.g., is a count variable). This suggests that a count data model, Poisson or negative binomial depending on the presence of overdispersion, would be appropriate. Nearly 99% of our county-storm observations, however, have a zero fatality count, which suggests the appropriateness of a zero-inflated regression specification. A zero-inflated model allows for over-dispersion from an excessive number of zero observations by assuming that the dependent variable is a mixture of a degenerate distribution with mass concentrated at zero and then either a Poisson or negative Binomial distributed variable (Cameron and Trivedi 1998, pp. 123–128). The model is estimated in two stages, with the first stage being a logit model to predict the probability of zero fatalities in a given county event and the second stage either a Poisson or negative binomial model of the count of fatalities in a given county event. Zero-inflated models have previously been applied to natural hazards fatalities by Kahn (2005), Long and Freese (2006), Kellenberg and Mobarak (2008), and Czajkowski and Kennedy (2010). For hurricane fatality data, a zero-inflated model makes intuitive sense given the role of mitigation, which would be difficult to account for directly. A zero fatality observation may occur in a particular hurricane if a high percentage of the population mitigates or if the hurricane fails to reach a threshold.

We select three factors that plausibly increase the probability of zero fatalities for a county observation, based on Tables 1, 2, and 3: (1) a dummy variable for secondary or tertiary counties to capture an indirect hit from the storm; (2) a dummy variable equal to one for wind speed less than or equal to 29 knots to capture a low wind event; and (3) a dummy variable for total rainfall less than or equal to 3 inches to control for low potential for freshwater flooding. To choose a threshold for low rain, we found the average rainfall for all counties that received rain. The average for that group was 2.9 inches of rain, so we used less than 3 inches of rain as a cutoff value for low rain. For wind speed, the average wind speed was 29 knots, so any speed below 29 knots was coded as low wind.

We include several variables to control for geography, socioeconomic characteristics, and a potential time trend in casualties in the count stages. We include the size of county in square miles as a control. Controlling for population density, a larger county should be more likely to experience a fatality. We add a dummy variable equal to 1 for coastal counties as well as a dummy variable equal to 1 for the identified affected landfall counties. We include dummy variables to control for secondary and tertiary counties; the coefficient on each of these variables measures the impact on fatalities relative to a primary county.

We include variables to control for county population density in thousands of persons per square mile and median household income in thousands of dollars in the year of the hurricane. A more densely populated county is expected to experience more fatalities. Previous international studies find that income reduces the lethality of natural hazards (Kahn 2005, Anbarci et al. 2005), and so we expect a negative sign for income. Finally, we include decade dummy variables to control for changes in the lethality over time. The 1970s are the omitted category, so the included decade variables measures the difference in lethality relative to a comparable hurricane in the 1970s. Decade dummy variables allow for a more general effect of time on lethality than a linear trend.

4 Econometric results

4.1 Overall fatalities

Table 6 presents our analysis of hurricane fatalities. The first column presents a zero-inflated Poisson (ZIP) specification of total fatalities with robust standard errors as the dispersion parameter alpha is not significantly different from zero. The lack of statistical significance of the dispersion parameter alpha suggests that the ZIP specification is preferred to a ZINB specification. A Wald test of the joint insignificance of our explanatory variables is easily rejected at the 1% level. The dummy variables for low rainfall and low wind events are significant in the logit estimate to explain zero fatalities with the expected sign, while the non-primary county variable fails to attain significance at the 10% level or better. All of the variables except the secondary county dummy, landfall county, and the coastal county dummy attain significance at the 10% level or better in the ZIP specification. Expected fatalities are almost five times higher in a tertiary than a primary county, and although insignificant, the point estimate indicates that fatalities are 130% higher in a secondary county. Controlling for storm conditions, fatality risk is greater away from the storm's center path. The decade dummy variables all indicate increasing lethality of hurricanes relative to the 1970s. Hurricanes in the later decades were 180 to 380% more deadly than in the 1970s, while the included decade dummy variables are not generally significantly different from each other. By contrast, Czajkowski and Kennedy (2010) found a reduction in fatalities over this period for fatalities in landfall counties. The increased lethality over time might indicate that inland hurricane risk has not received as much focus as coastal areas. The area of a county significantly increases fatalities—for a given population density, counties with larger land area has more people at risk, and this increases the expected number of fatalities. Higher-income counties experience significantly more fatalities, in contrast to international findings. The difference in income observed internationally is much greater than between counties within the United States, which might explain this difference. Wind and rainfall both significantly increase expected fatalities, validating our construction of these variables and confirming the univariate comparisons in Tables 4 and 5. Storm characteristics are important drivers of fatalities, as a one-knot increase in wind speed and a one-inch increase in rainfall increase expected fatalities by 4 and 28%, respectively. A one standard deviation increase in wind and rainfall increases expected fatalities by 103 and 84%, respectively.

To illustrate the effect of local storm conditions on fatalities, we use the coefficient estimates to construct expected fatalities as functions of wind and rainfall for an average county, meaning with all other explanatory variables set at their mean values. Figures 5 and 6 graph expected fatalities as functions of wind speed and rainfall, respectively.

Table 6 Fatality estimation results

	Total	Freshwater	Wind
Independent variable			
Secondary county	0.850	−0.046	1.425
	(0.551)	(0.702)	(1.139)
Tertiary county	1.672***	1.206	2.533**
	(0.609)	(1.534)	(1.251)
1980 decade dummy	1.576***	0.454	1.879**
	(0.428)	(1.080)	(0.822)
1990 decade dummy	1.451***	0.402	2.138*
	(0.405)	(1.063)	(1.209)
2000 decade dummy	1.022**	0.548	1.740*
	(0.462)	(1.133)	(1.042)
Landfall county	0.129	−0.364	0.026
	(0.470)	(0.812)	(0.578)
Wind speed	0.039***	0.021	0.068***
	(0.007)	(0.015)	(0.010)
Total rainfall	0.250***	0.371***	−0.066
	(0.038)	(0.090)	(0.115)
County square miles	0.005***	0.009	0.005
	(0.002)	(0.008)	(0.005)
Coastal dummy	0.141	−1.319**	−0.049
	(0.383)	(0.568)	(1.086)
Population density	0.985	2.390*	0.737**
	(0.658)	(1.328)	(0.370)
Median income	0.0382***	0.0432**	0.0156
	(.0123)	(.0191)	(.0274)
Constant	−9.677***	−8.703***	−10.287***
	(1.327)	(1.915)	(1.957)
Zero-inflated logit			
Non-primary county	0.875	0.309	1.233
	(0.650)	(0.571)	(0.966)
Low wind	0.730**	0.920	0.219
	(0.370)	(0.561)	(0.741)
Low rain	1.258***	1.642***	1.340***
	(0.390)	(0.535)	(0.510)
Constant	0.127	1.867***	0.783
	(1.083)	(0.480)	(0.801)
Alpha	2.191	0.000	0.000
	(1.683)	(1.273)	(0.915)
Log pseudolikelihood	−533.9	−232.9	−207.6
Wald chi2	159.7	174.3	231.3

Robust standard errors are in parentheses

Observations = 9,326

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

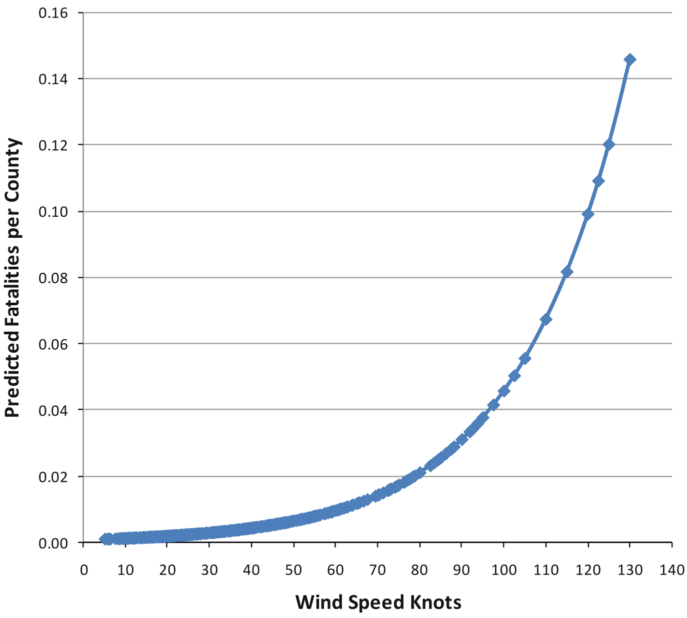

Fig. 5 Predicted rates of county fatalities by wind speed

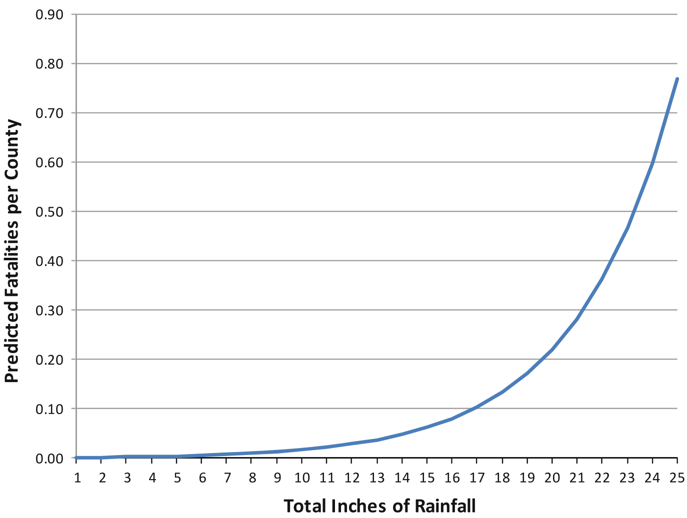

Fig. 6 Predicted rates of county fatalities by amount of rainfall

Expected fatalities per county in Fig. 5 exceed 0.02 at around 80 knots, which is near the threshold for a category 2 hurricane. Expected fatalities per county in Fig. 6 exceed 0.1 for counties at around 17 inches of total rainfall. Comparison reveals that the most extreme rainfall events in our sample produce a higher expected fatality count than the extreme wind events: the highest observed wind speeds (135 knots) result in about 0.15 fatalities in an average county, while 0.75 fatalities are expected with the maximum observed rainfall of 25 inches.

4.2 Inland flooding fatalities

We now analyze determinants of the two most frequent types of hurricane fatalities, freshwater drowning and wind, to see whether different factors drive these two types of hurricane deaths. Analysis of the determinants of fatalities by cause can help target efforts by the public and policy makers to reduce each type of threat. Freshwater drowning and wind account for 75 and 60 fatalities, respectively, or together about 75% of fatalities in our path county dataset. The remaining types of fatalities are too infrequent for a separate analysis.

The second column of Table 6 reports a ZIP model of freshwater-drowning fatalities with robust standard errors as again the dispersion parameter alpha is not significantly different from zero. A Wald test rejects the joint insignificance of our explanatory variables at the 1% level. Only a low-rain event attains significance in the logit regression, indicating that a county with less than the median rainfall was more likely to have no freshwater-drowning fatalities. The lethality of freshwater appears to have increased over time, as the point estimate of the decade dummy variables indicates a 50–70% increase in lethality relative to the 1970 s, but these variables fail to attain significance. Wind is no longer statistically significant in either stage of the freshwater-drowning analysis. Rainfall is highly significant and is the primary driver of flood fatalities, in the poisson stage. A one-inch increase in rainfall increases expected freshwater-drowning fatalities by 45%, which is significantly greater than the 28% increase in overall fatalities. Expected freshwater-drowning fatalities are higher for inland than coastal counties, with fatalities 73% lower in a coastal county. Higher population density and income each significantly increase expected freshwater-drowning fatalities, with the income result consistent with the findings for overall fatalities.

4.3 Wind-related fatalities

The third column of Table 6 reports the analysis of wind fatalities also using a ZIP model of freshwater-drowning fatalities with robust standard errors as again the dispersion parameter alpha is not significantly different from zero. Wind lethality has increased sharply over time as each decade variable attains significance and increases in expected wind fatalities by 470–750% relative to the 1970s. Wind is an important determinant of wind fatalities, a one-knot increase increases expected wind fatalities by 7%, compared with the 4% increase for total fatalities. Wind fatalities appear to be greater away from the center of the storm path when controlling for wind speed. Expected wind fatalities are 310% greater in a secondary county and more than twelve times greater in a tertiary county than the central path county, although the former effect is not statistically significant. Population density also significantly increases wind fatalities.

We applied a simple decay rate (100–75–50) to construct wind speed values for the secondary and tertiary counties in our storm paths. As discussed earlier, existing research on hurricane wind fields could justify other patterns of decay. The important question for an analysis of vulnerability is whether a different plausible wind field would affect our inferences regarding the influence of wind on fatalities. To explore this, we imputed wind speed values for the secondary and tertiary counties using a variety of different decay rates and then reestimated the fatality regressions with these alternate wind speed variables.

Table 7 Sensitivity of wind field estimates

Decay pattern	100–75–50 (baseline)	100–50–25	100–100–67
Secondary county	0.850	1.72***	0.144
Tertiary county	1.672***	2.65***	1.04*
Wind speed	0.0386***	0.0438***	0.0333***
Log pseudolikelihood	−533.9	−531.6	−536.4
Wald chi2	159.7	156.3	157.7
Mean wind speed	29.3	21.4	35.9
Standard deviation wind speed	18.4	17.9	20.9

Coefficient values only are presented

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Table 7 reports some illustrative results for two alternative decay rates, along with our baseline case for comparison. The same full zero-inflated models were estimated as in Table 6, but only the results for the secondary and tertiary county and wind speed variables are reported in Table 7; the results for the other variables in each alternative specification do not differ in any important manner from Table 6.

One alternative wind field applies a faster decay rate and assigns values of 50 and 25% of the primary county value to the adjacent secondary and tertiary counties, while the second alternative assigns wind speeds of 100 and 67% for the secondary and tertiary counties. Comparison reveals that assigning more slowly decaying (rapidly decaying) wind speeds to the adjacent counties decreases (increases) the point estimates of the secondary and tertiary county dummy variables. For example, when secondary counties are assigned a wind speed of 50% of the primary county value, the secondary county variable attains significance, and the point estimates indicate a 450% increase in expected fatalities, controlling for wind speed, but when the secondary counties are assigned the same wind speed as the primary county, expected fatalities are only 15% higher in the secondary counties, and the point estimate is not significant. The point estimate of a one-knot increase in wind speed is larger when wind speeds are imputed to decline more rapidly. Thus, the secondary and tertiary county variables seem closely related to the wind field estimate applied. This analysis indicates that a more precise measurement of the wind field actually observed across the inland portion of the storm path could improve analysis of the determinants of fatalities.

5 Conclusions

Understanding the determinants of hurricane fatalities holds the key to reducing risk in the future. Existing studies have documented a decline in the lethality of US hurricanes over time (Kunkel et al. 1999; Rappaport 2000; Sadowski and Sutter 2005; Blake et al. 2007), which likely reflects the value of improvements in hurricane forecasts and warnings in allowing for timely evacuations (Rappaport 2000; Willoughby et al. 2007). Hurricanes, however, are multi-faceted threats, which extend well inland from coastal evacuation zones. Rappaport (2000) found that the majority of tropical cyclone-related fatalities between 1970 and 1999 occurred inland and were due to freshwater flooding. Czajkowski and Kennedy (2010) found that 80% of hurricane fatalities between 1970 and 2007, excluding Hurricane Katrina, occurred outside of landfall counties.

We have begun an extension of analysis of the determinants of hurricane fatalities to consider the type of fatality and their location. We have cast a broad net to explore hurricane-related fatalities (about 150 counties are in the average hurricane path), and yet as many fatalities for which the county could be identified occurred outside of as in our path areas, highlighting the geographical diffusion of fatalities. We have constructed county-level wind and rainfall variables to capture the variation in storm conditions across the storm area, as storm characteristics at landfall are obviously insufficient for this purpose. These variables perform very well, as a one-inch increase in rainfall and one-knot increase in wind speed increase expected fatalities by 28 and 4%, respectively. Furthermore, rainfall and wind speed have a greater marginal effect on freshwater-drowning and wind fatalities, respectively, than total fatalities and much less effect on the other type of fatality. The county-level storm variables can serve as the basis for future research to explore the effect of demographic and economic variables in addition to storm strength on casualties.

Overall fatalities and particularly wind deaths have increased since the 1970s, even with Hurricane Katrina excluded. This result contrasts with recent papers that found a downward trend (Sadowski and Sutter 2005; Czajkowski and Kennedy 2010). Our finding is not necessarily inconsistent with prior results. Sadowski and Sutter (2005) examine fatalities from 1940 to 1999, and the bulk of the reduction in lethality they document occurred by 1970, the start year for this study. And Czajkowski and Kennedy (2010) examined only fatalities in landfall counties. Media attention, evacuations, and public education efforts to reduce hurricane fatalities focus on coastal areas. Threats to life as a hurricane moves inland have received less attention. Future reductions in hurricane lethality will likely stem from addressing the inland threat.

The significance of the county-level wind and rainfall variables suggests the value of our disaggregated approach to hurricane fatalities. Our research here is best understood as laying out a new direction for hurricane fatalities research as opposed to completing the analysis. We have noted a number of limitations of the data analyzed in this study, which in turn illustrated directions for future research. In fact, given the limitations of the data, the major result of this study should probably be viewed as the ability of the rainfall and wind speed variables to explain freshwater-drowning and wind-related fatalities across the hurricane path. We have experimented here with different simple formulas to impute wind speeds based on observations along the inland path of the center of the storm, and future research could consider additional alternatives, including asymmetric wind fields or patterns of decay, which vary based on distance inland. Our interpolated rainfall variable was the mean value for the county but could alternatively use the maximum interpolated result. Future research could also attempt to incorporate other factors that might affect the severity of flooding, like rainfall prior to the hurricane, the presence of rivers or streams subject to flooding, and the elevation change in a county. Incorporating tropical storms into the analysis may also be useful in this regard given that some have resulted in major flooding and loss of life. And the included demographic variables could be expanded to consider other factors commonly associated with natural hazards vulnerability. All of these extensions would allow researchers to better understand the complex nature of the hurricane threat.

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